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Title	Phased-array-antenna control using liquid crystals
Authors	Riza, Nabeel A.
Publication date	1993-02-26
Original Citation	Riza, N. A. (1993) 'Phased-array antenna control using liquid crystals', Proceedings of SPIE, 1790, Analog Photonics, Fibers '92, 1992, Boston, MA, United States, 26 February 1993, doi: 10.1117/12.141721
Type of publication	Conference item
Link to publisher's version	10.1117/12.141721
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Nabeel A. Riza, "Phased-array-antenna control using liquid crystals," Proc. SPIE 1790, Analog Photonics, (26 February 1993); doi: 10.1117/12.141721

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Phased array antenna control using liquid crystals

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ABSTRACT

A novel optical control system using nematic liquid crystals and acousto-optic devices is introduced that can provide compact, lightweight, low cost, transmit/receive mode, high performance (> 8 bits), truly analog, amplitude and phase control for large phased array antennas. The system provides independent amplitude and phase calibration and control capabilities across the array.

2. INTRODUCTION

Most present-day state-of-the-art phased-array systems use modulo-2π phase-based control implemented by digitally controlled microwave phase shifting devices. For large arrays (e.g., 5000 elements), these all electronically controlled radar systems become hardware intensive, resulting in large, heavy, and extremely expensive systems. While true-time delay type optical systems are geared towards the future wide instantaneous bandwidth radars requiring wideband signal processing capabilities, research into optoelectronic phase-based systems is directed towards realizing a small, lightweight, low cost, high performance radar system for replacing the expensive and cumbersome all-microwave technology based present-day narrowband phased-arrays. Important consequences of a future low cost, compact, phased-array controller include large scale commercial applications such as air traffic radars, and the possibility of large spaceborne/airborne and ground-based mobile phased array antennas.

Critical for achieving high performance from a phased-array is the number of active antenna elements in the array, and the precision and resolution of the amplitude and phase control for the antenna drive signals. Typically, due to transmit power efficiency considerations, the power amplifiers in the transmit modules operate at saturated power levels for maximum efficiency. If a tapered phased-array excitation is required to achieve a certain beam radiation pattern, it is done by electronically controlling the signal levels at the final power amplification stages of the array. In this way, high transmit mode power efficiency can be maintained. Thus, if array amplitude tapering is introduced, a critical factor in obtaining precision amplitude control is the resolution of the level controls achieveable at the power amplifier stages. Note that antenna beam shape control, nulling, and steering can be achieved by a combination of array amplitude and phase control, and also by array phase-only control. If phase-only control is used, and the transmit power amplifiers operate at saturated power levels, the signal phase control stability and precision becomes the key concern for achieving high performance. Thus, because phase control is required in all beam control modes, the resolution and stability of the microwave signal phase shift is of utmost concern. In effect, if a high performance, low side-lobe radar is required, better than 6-bit phase control is required for the array.

As mentioned earlier, the number of elements in an array is also a very important design factor. In particular, the greater the number of elements in the array, the better the spatial resolution of the antenna beam, which in-turn provides a higher angular tracking resolution for the radar. In addition, the greater the number of elements, the greater the radar overall transmit power, leading to a higher receive-mode sensitivity and longer radar search ranges. Moreover, with precision (> 6 bit) phase control, the number of beams scanned over a certain region in space can be increased. A typical high performance array can have as many as 5000 active elements, although this number is not an upper limit. A key factor that limits the size of an array is the cost per active element. For present-day microwave phase-shifter based phased arrays, this cost includes active and passive components such as the microwave phase shifting device, the transmit/receive (T/R) module amplifiers, the digital control network for the phase shifters, the microwave cabling for signal distribution, microwave power splitters and combiners, and T/R module switches. It is critical that for future large arrays to be possible, the cost per active element control hardware be low, regardless of whether the control mechanism is optical, electronic, or optoelectronic.

Most phased-arrays use modulo-2π phase-based control. In this paper, we will describe a novel high performance optoelectronic control system for phase-based phased arrays that has the potential for providing independent amplitude and phase control for the next-generation low cost, compact, light weight, high-performance phased array antennas.

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2. THE HIGH PERFORMANCE OPTICAL CONTROL SYSTEM

Fig.1 shows the novel NLC/AOD-based high performance optical control system for phase-based phased-array radars. As signal phase stability is a critical requirement for radar applications, it is important that the optical control system possess excellent stability. For microwave band (< 8 GHz) signal generation, this excellent stability can be provided by the in-line additive acousto-optic (AO) interferometer proposed and demonstrated in earlier work [1-4]. To demonstrate 0-2π phase control via the NLC-based phased array controller, a version of the system in Fig.1 is set-up in the laboratory [5]. A linearly (p or vertically) polarized beam from a 10 mW He-Ne laser is expanded and spatially filtered using a microscope objective/pin-hole assembly. The expanded light is collimated by a 25 cm focal length (FL) spherical lens. The collimated beam passes through an iris that forms a 5 mm diameter pencil beam that is incident at Bragg angle on the acoustic column of a Bragg cell/AOD called AOD1. This experiment uses flint glass radio frequency (rf) band AODs with 70 MHz center frequencies, 10 μsec time-apertures, and 40 MHz bandwidths. AOD1 and AOD2 are driven by 8.8 Vp-p at 50 Ω, 60 MHz rf signals. The +1 order diffracted beam and the undiffracted DC light from AOD1 are 1:1 imaged on to the second Bragg cell called AOD2, using two FL=15 cm spheres. The +1 order beam passes through a twisted nematic liquid crystal (TN-LC) cell that rotates the beam polarization by 90 degrees, thus converting the p-polarization to a s or horizontal polarization. A half-wave plate can also be used instead of the TN-LC cell. The DC light from AOD1 is also Bragg matched to AOD2, and generates a -1 order beam that is collinear with the +1 order from AOD1. Part of the +1 order beam from AOD1 passes essentially uneffected through AOD2. Thus, after AOD2, the -1 and +1 order beams are collinear, with mutually orthogonal p and s polarizations, respectively. These collinear beams pass through a parallel-rub, birefringent mode, single pixel, NLC cell, that is responsible for generating the required modulo-2π phase-shifts for the antenna control.

The desired analog phase control is achieved by the analog nature of the electrically controlled motion of the birefringent NLC molecules. Because the NLC molecular director (or long axis of the molecules) is aligned along the p polarization direction of the incident -1 order light, only the -1 order beam sees a changing index of refraction as the NLC molecules rotate due to an applied electric field. The +1 order beam continues to see a fixed index of refraction corresponding to the ordinary (or along the short axis of the molecule) index of refraction as the applied field across the NLC cell varys. Next, the phase shifted p polarized beam, and the unmodulated s polarized beam pass through a polarizer that is oriented at 45° to the p and s directions. This polarizer acts as an optical adder, combining the in-line components from the +1 and -1 order beams. A 10 cm FL spherical lens is used to focus the collinear light beams on-to a Hamamatsu Model S 2381 avalanche photo-diode (APD) operated at a bias of 185 V. The unwanted beams are spatially filtered by a DC block. Both Bragg cells are driven by the same signal that has a frequency that is half the desired antenna carrier frequency. This is because, on heterodyne detection of the +1 and -1 order beams, the doppler shifts from the two beams add to give the desired antenna frequency. The 120 MHz signal from the APD is amplified by a 40 dB gain power amplifier. Fig.2 shows the oscilloscope traces indicating phase-shifts that are obtained for the 120 MHz signal by varying the NLC applied voltage. Using a 1.0 to 3.8 V change in applied voltage, 0-3π phase control is easily achieved using the 6 μm thick NLC cell. A 348 mVp-p at 50 Ω (or - 5.19 dBm) signal is available after amplification. The 120 MHz signal showed a carrier-to-noise ratio of 116.8 dB/Hz at +1 MHz offset (Fig.3), and a dynamic range of 55.5 dB at +1 MHz offset (see Fig.4), using a spectrum analzer with a noise resolution bandwidth (RBW) of 300 KHz. For comparison, the 60 MHz signals available from a Wavetek signal generator, that are driving the AODs showed a carrier-to-noise ratio of 124 dB/Hz at +1 MHz offset using the same analyzer RBW. Thus, with a high performance signal generator used for radars, much better signal quality is expected from the optical system.

3. NLC-BASED CONTROL SYSTEM ISSUES

To generate the signals for a large (e.g., 5000 element) phased array, the two collinear beams after AOD2 pass through a beam expander that generates spatially expanded, collinear beams that illuminate a two dimensional (2-D) array of parallel rubbed NLC pixels in NLC Array 1 (see Fig.1). This NLC array provides the phase control for the output electrical signals. The light then passes through the polarizer at 45° , another 2-D NLC array called NLC Array 2, an appropriately oriented polarizer, and a 2-D lenslet array, before entering a 2-D fiber array. The NLC Array 2 provides the desired amplitude control for the electrical signals generated at the output of the processor. If a TN-LC array is used for the amplitude control NLC Array 2, the output polarizer before the lenslet array is crossed to the 45° oriented polarizer before NLC Array 2. Note that the NLC molecules on the input or front side of NLC Array 2 are aligned with the 45° oriented polarizer. There is a 1:1 correspondence between the antennas in the phased array and the NLC pixels in the two NLC arrays. At the end of each fiber is an optical detector that generates the appropriately phased antenna signal via heterodyne detection of the two beams carried in the fibers. With no voltage

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applied to the TN-LC pixels, the light passes through to the output fibers, essentially unattenuated. The amount of linear polarization rotation of the incident light that is passing through the TNLC pixel can be controlled by applying a voltage to the TN-LC pixel. When seen through the output polarizer (before the lenslet array), the light amplitude can be controlled, implying that the amplitude of the rf signal generated by the photo-diode at the end of the fiber can also be adjusted by the TN-LC pixel. Both NLC arrays have an identical number of pixels, providing independent amplitude and phase control for all the elements in the phased array.

To generate microwave signals from the optical system, GHz band Bragg cells are used in the system. Carrier frequencies up to 7-8 GHz are possible using wideband cells [6]. Because GHz AODs are small (e.g., 0.1 mm aperture) optical devices that generate relatively large (e.g., 20°) Bragg deflection angles between the diffracted and DC beams, the optical path before AOD2 can be made fairly short (< a few cm). This further improves system stability, in addition to making a compact design. The architecture has no moving parts, and allows very fast (0.2 μsec) antenna carrier frequency agility over a very wide (2 GHz) frequency range provided by the wide bandwidth of the Bragg cells and appropriate beam expansion of the interfering p and s-polarized beams. Note that as the frequency of the signal driving the AODs changes to alter the antenna carrier frequency, the +1 and -1 order beams continue to remain collinear, a condition required for the NLC-based phase control operation in this architecture.

Microwave and millimeter wave signal generation can also be accomplished via frequency up-conversion via electronic mixing and bandpass filtering. In this scenario, the mm-wave/microwave signal from a stable radar signal source is used to directly/indirectly modulate a laser source that feeds several optical fibers. Each fiber then terminates at a photodiode located at a sub-array at the antenna site. The photodiode generates the mm-wave/microwave signal that is electrically distributed to the several T/R modules in the sub-array. The electrooptic processor that provides the phase and amplitude controlled signals for the antenna array is based on rf Bragg cells, much like the experimental processor described in this paper. Thus, each photodiode at a T/R module location generates an rf (e.g., 100 MHz) signal that is then electronically mixed with the mm-wave/microwave signal to generate a double sideband signal, which after bandpass filtering, leaves a single sideband signal at the desired radar carrier, with the appropriate amplitude and phase values. Because rf Bragg cells have much higher diffraction efficiencies per watt of AOD drive power when compared to GHz band devices, there are advantages in terms of overall system power efficiency and lower output signal non-linearities to be gained by using this external mixing technique. On the other hand, if increased hardware complexity and cost are to be minimized, and small (e.g. 1000 element), short to medium target range microwave (< 8 GHz) phased arrays have to be controlled using a compact, lightweight, low cost control system, the GHz band electrooptic processor can be used for the antenna control. It is important to note that because the system is based on an almost common-path interferometer, broadband, high power (e.g., 1 W) laser sources (e.g., diode lasers, diode laser arrays, air-cooled ion lasers) can be used in this system, depending on the radar requirements, and optical system type.

Typical high performance phased array radars require microwave phase-shifter response times of 1-10 μsecs, with beam scanning rates of > 200 beams/sec corresponding to < 5 msec transmit-receive (T-R) beam sequences [7-8]. These phased arrays implement beam scanning by resetting each phase shifter to the new phase setting before each new T-R beam sequence, thus implementing antenna scan control in a serial fashion (see Fig.5). For radars requiring this very fast several hundred beams/sec scanning speeds, a unique time-multiplexed radar beam scanning technique can be used to counter the slow several milliseconds response of the NLCs. Keys to this approach include using a pair of NLC arrays (called NLC SLM 1 and NLC SLM 2 in Fig.6; SLM: spatial light modulator) instead of one NLC array, the several millisecond dwell time of fast beam scanning state-of-the-art radars, and the a priori or deterministic nature of radar beam scanning. Here, each NLC SLM is a cascade of two NLC arrays, one for phase control, and one for amplitude control. Thus, a complete system would have two NLC arrays for phase control, and two NLC arrays for amplitude control. Note that from a fabrication and assembly point-of-view, the two arrays for phase control can be on a single glass substrate; in effect, a single parrallel-rub NLC SLM. The same is true for the amplitude control NLC arrays. This time multiplexed sequential control arrangement enables one beam to be scanned as determined by NLC SLM 1, while the NLC SLM 2 is switching to set up the scan for the next beam; when the next beam is scanned, NLC SLM 1 switches to set up for the next beam scan and so forth. Note that the several milliseconds dwell time of an antenna beam position corresponding to NLC SLM 1 is adequate for setting up NLC SLM 2, which sets the phase values required for the next desired beam position. This is because NLCs can be made to switch in several milliseconds. Note that for this time-multiplexed scanning method, the next sequential beam scan position has to be known. Because of the a priori or deterministic nature of radar beam scanning, knowing the next beam position is not a problem because a radar is programmed to follow a specific known/desired scan path. Thus, all the desired beam scan positions are known, implying that a computer stored with all the desired NLC SLM

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phase and amplitude configurations can be used to implement the time-multiplexing beam scanning operation. Moreover, even while operating in the tracking mode, a computer calculates the most likely target path based on earlier scans, and at least two known scan beams are used to determine the possible target trajectory/flight path. Thus, based on known beam scan positions, the echoed data can give an accurate idea of the target track, implying that the time-multiplexed scanning technique is also applicable for search and track radar modes. Switching between the two NLC SLMs in an optical architecture (similar to the single NLC SLM design of Fig.1) can be accomplished by fast response (e.g., 1-10 ns) laser, electro-optic, or microwave switching, leading to very small (1-10 nsec) radar dead times, where dead time is the duration when the radar is unable to detect targets. This can lead to higher receive sensitivity for the radar. In general, the novel time-multiplexed radar beam scanning approach can be applied to any NLC-based radar control system, including the fiber or free-space version of the time-delay control system introduced recently [9-11].

4. SUMMARY

This paper has introduced a novel NLC-based optical control system for phased-array antennas. The system generates the signal sets for both transmit and receive modes, with receive mode processing based on electronic mixing of the receive signal set with a replica of the transmit signal set available from the optical system, and low pass or IF filtering [2-3]. Fig.7 shows a typical T/R module for the optically controlled phased array radar, while Fig.8 shows a typical system scenario. The NLC-based optical control technique is reversible in nature. In other words, essentially the same system hardware is used for transmission as well as reception. In fact, when switching from the transmit to the receive mode for a particular beam direction, the NLC phase settings are not changed, only the microwave switch in the T/R module is switched to the receive position. In this way, the low power receive signals from the antenna elements are immediately converted to baseband or the intermediate frequency (IF) at the T/R module site, and do not have to flow as microwave signals through numerous microwave combiners and waveguides, as is done in present electronically controlled arrays. This feature can reduce system noise and increase receiver sensitivity. The IF signals on receive are generated by resetting the AOD drive signals to a new frequency that is offset by half the desired IF frequency. For example, for a 1 GHz carrier on transmit, the AODs are driven by 500 MHz signals. For a 60 MHz IF on receive, the AODs can be driven by 470 or 530 MHz signals.

The NLC phase control technology is well suited for large (e.g. 5000 element) phased-array applications, in particular, when considering the low cost per NLC pixel. For instance, for a planar array with 1,024 active elements, a pair of 64 X 32 pixel NLC SLMs are required. If the antenna array size is increased by nearly 5 times to 5000 active elements, a pair 100 X 100 pixel NLC SLMs are needed. Compared to display-type applications where 1000 X 1000 pixel arrays are desired for high performance, the phased array antenna application requires small (< 100 elements/line) NLC SLMs. Because of the much smaller number of NLC pixels to be fabricated and electrically addressed (perhaps with a thin film transistor/pixel), higher quality and faster frame rate devices can be built for the phased array application. Instead of using the slower multiplex addressing methods that have been used for the very large NLC display arrays, it might be possible to use direct electrical addressing (a wire/pixel) to obtain much faster frame rates without causing a bottleneck of wires.

5. CONCLUSION

The in-line additive design of the proposed optical control systems leads to high interferometric stability. Another very important capability of NLC-based phase control is the high resolution (> 8 bits), analog nature of the phase and amplitude control mechanism. This feature can provide phase and amplitude error calibration for large arrays, providing low sidelobe radiation patterns. NLC based control can give fast 200 beams/sec antenna scanning rates using a novel time-multiplexed antenna beam scanning approach. One feature of the optical control system is its ability to scan the antenna carrier over a very wide frequency range (e.g., 2 GHz when using GHz band AODs). Intra-pulse beamforming is possible because the carrier and phase of the microwave signal are independently controlled by the optical system.

The maturity of present-day NLC commercial display technology including highly developed NLC fabrication procedures are key to the low cost, high performance, low control power, large array control nature of the proposed radar control system. The proposed amplitude and phase control technique is essentially carrier frequency insenstive, and can be extended to mm-wave radar systems. In addition, very compact (e.g., 10 mm X 10 mm) NLC arrays can control very large (e.g., 5000 element) phased arrays using extremely compact (< 12 inches length), light weight (< a few kg) optical control systems. Fig.9 shows a 1500 element (30 X 50) parallel-rub NLC array fabricated at GECRD with support from the USAF Pilot Programs. Future work involves testing this postage stamp size device

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in order to generate phase control for a 750 element radar. In addition, extensions to millimeter wave signal generation and phase control will be described in future work. Note that for satellite phased array antenna applications, very fast antenna beam reconfiguration times are not required, and the time-multiplexed radar beam scanning approach may not have to be used. In conclusion, Table 1 compares the proposed optically controlled phased array radar system with conventional electronically controlled phased array antennas.

6. ACKNOWLEDGMENTS

Support from GECRD and GE Aerospace is greatly acknowledged.

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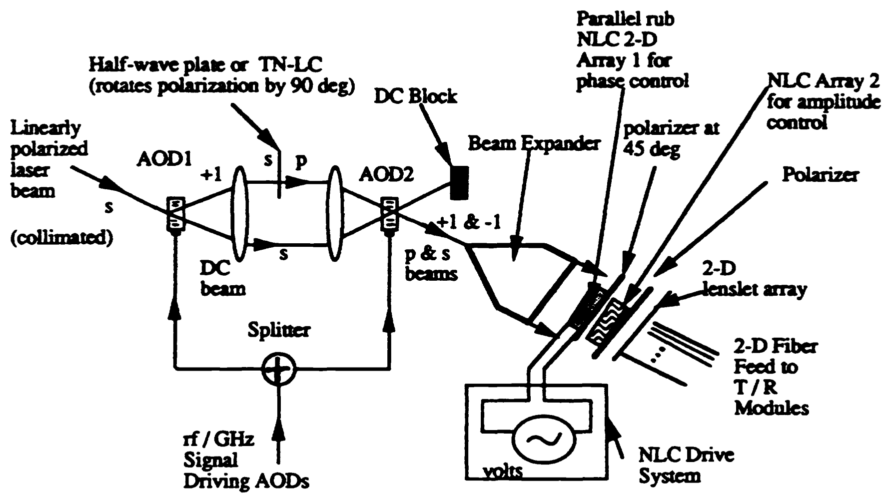

Fig.1 The high performance electrooptic control system for phased array antennas that provides independent signal amplitude and 0-2π phase control.

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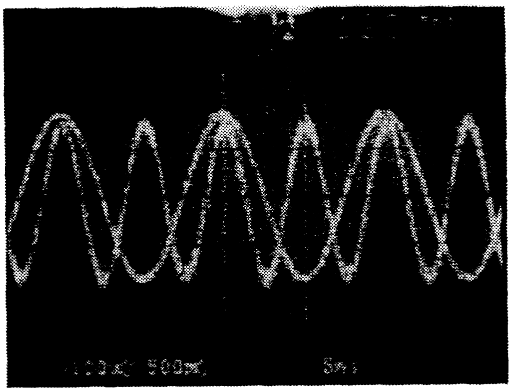
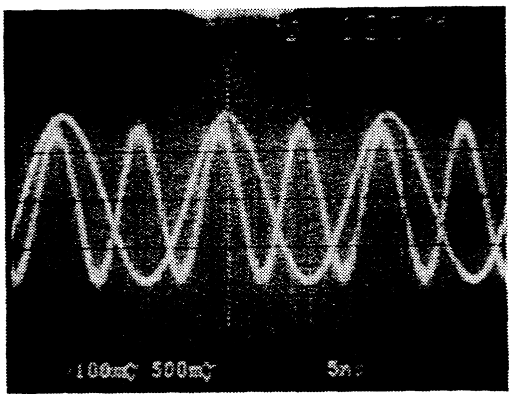
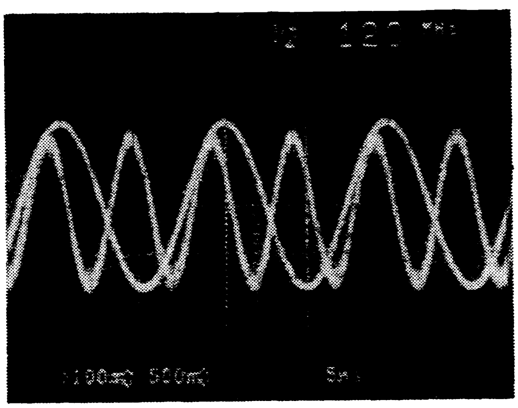
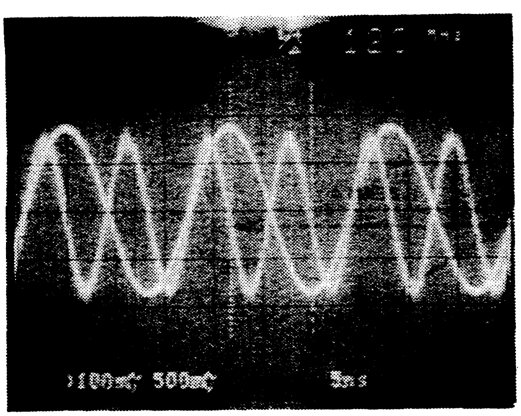
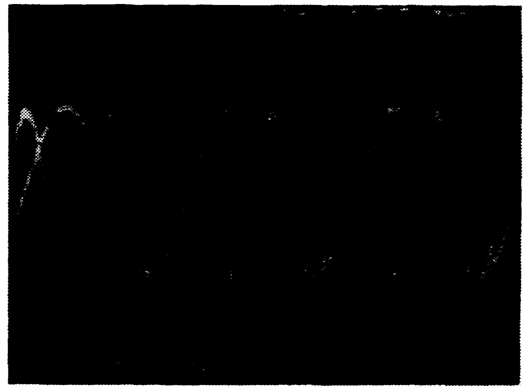
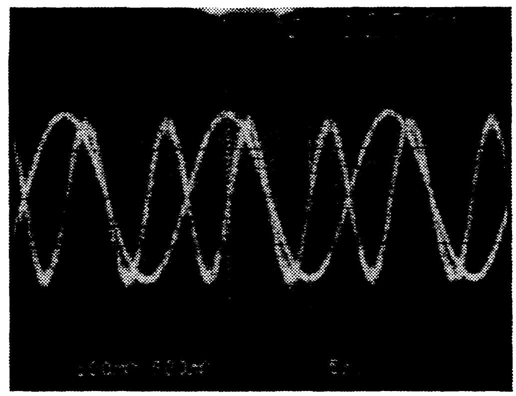
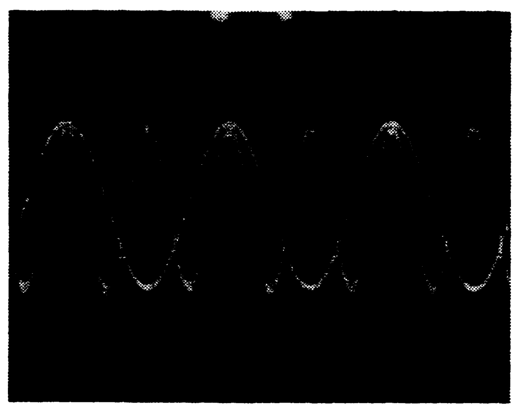

Fig.2 Oscilloscope traces showing the NLC-based phase control for a 120 MHz carrier (scale: 100 mV/div at 50 Ω). The 60 MHz signal (scale: 500 mV/div at 50 Ω) is the reference signal, that also drives the AODs. Time scale: 5 ns/div

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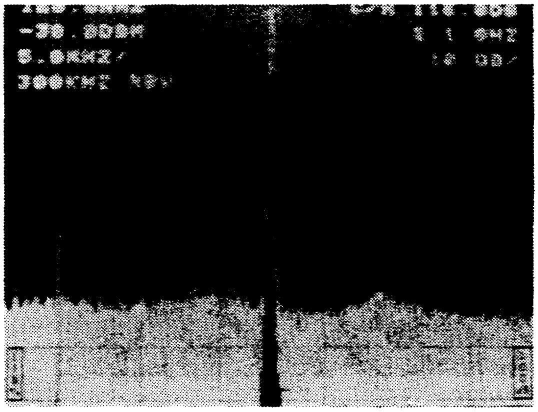

Fig.3 Spectrum analyzer trace showing a carrier-to-noise ratio of 116.8 dB/Hz at +1 MHz for 120 MHz rf signal output from optical processor. Analyzer RBW = 300 KHz

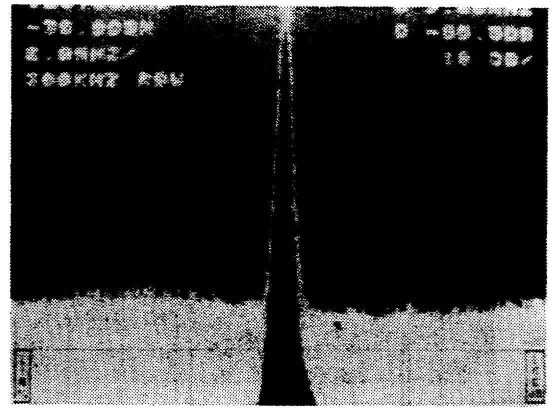

Fig.4 Spectrum analyzer trace showing a dynamic range of 55.5 dB at +1 MHz for 120 MHz rf signal output from optical processor. Analyzer RBW = 300 KHz

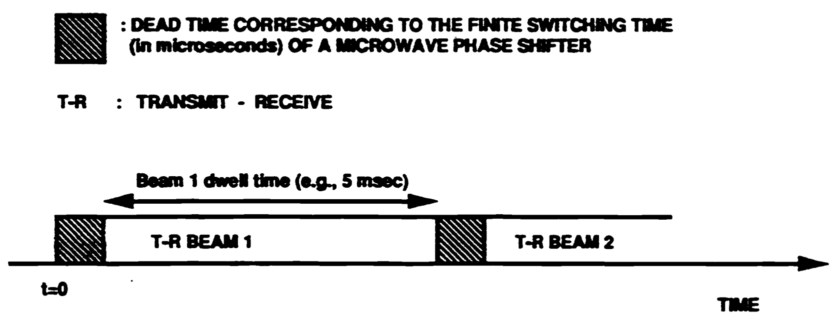

Figure 5. Present-day beam scanning technique for state-of-the-art phased array radars.

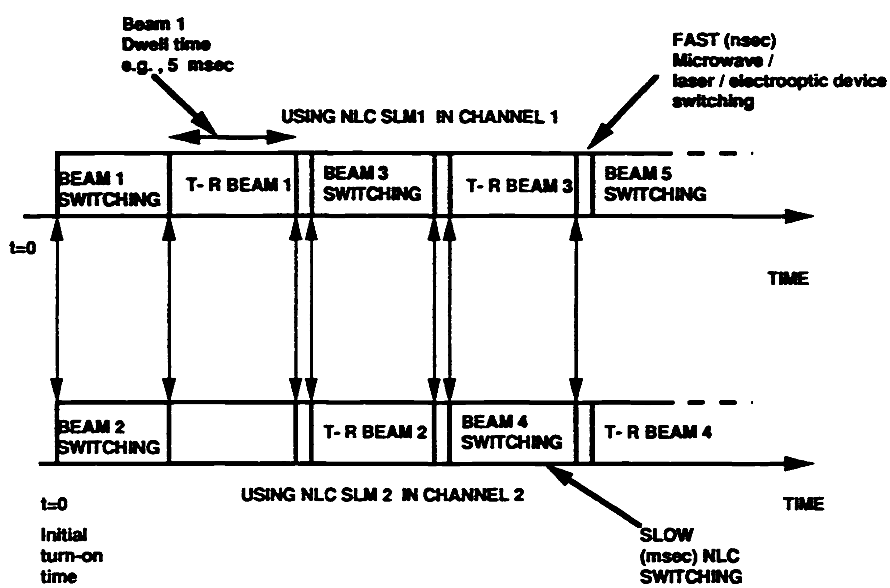

Figure 6. The novel time-multiplexed fast (e.g., 200 beams/sec) scanning technique that can result in very small (1-10 nsec) radar dead times.

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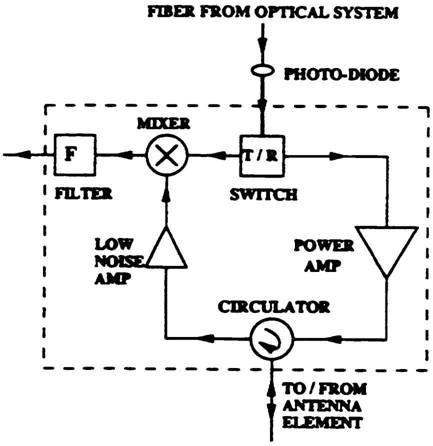

Figure 7. A typical transceiver module for an antenna element controlled by the optical system.

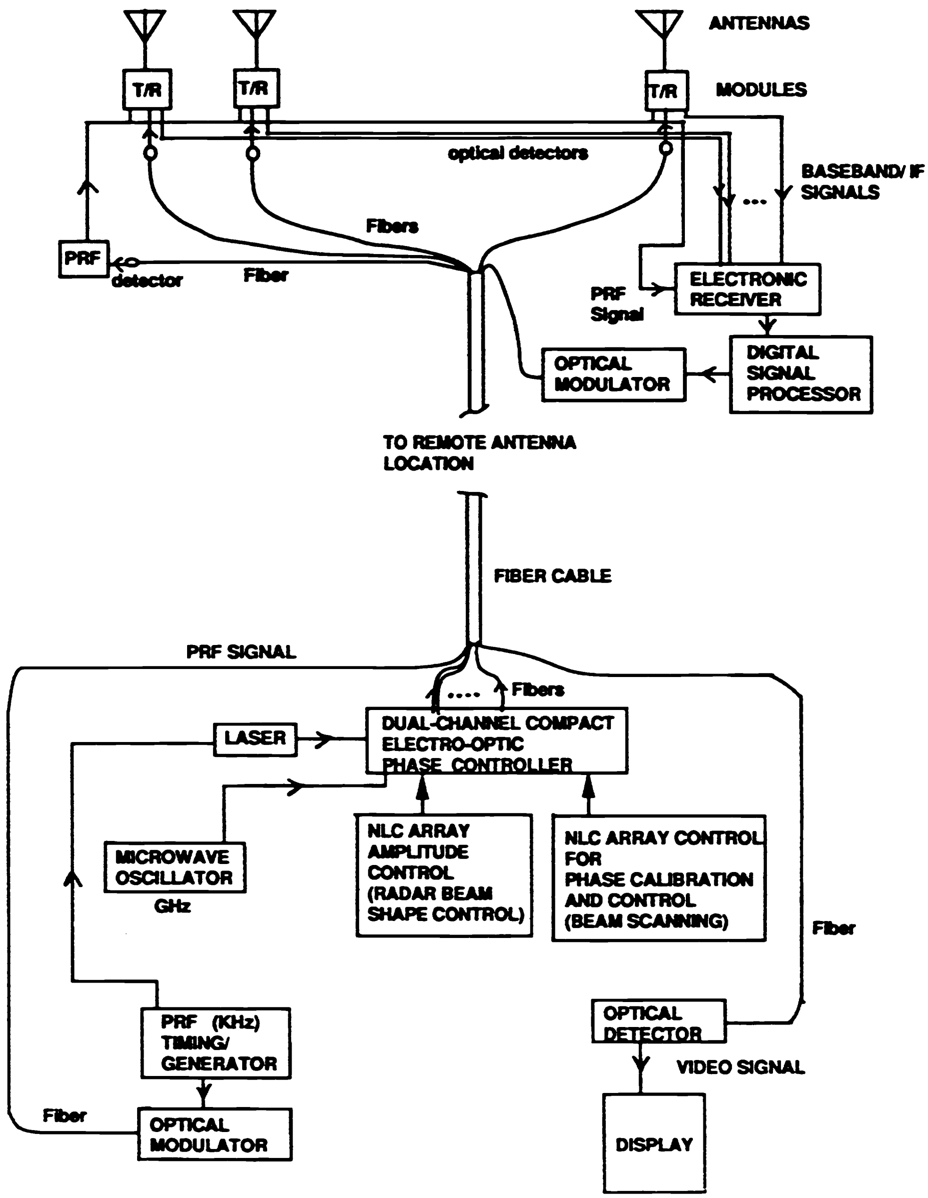

Fig.8 A typical system scenario for the optically controlled phased array radar.

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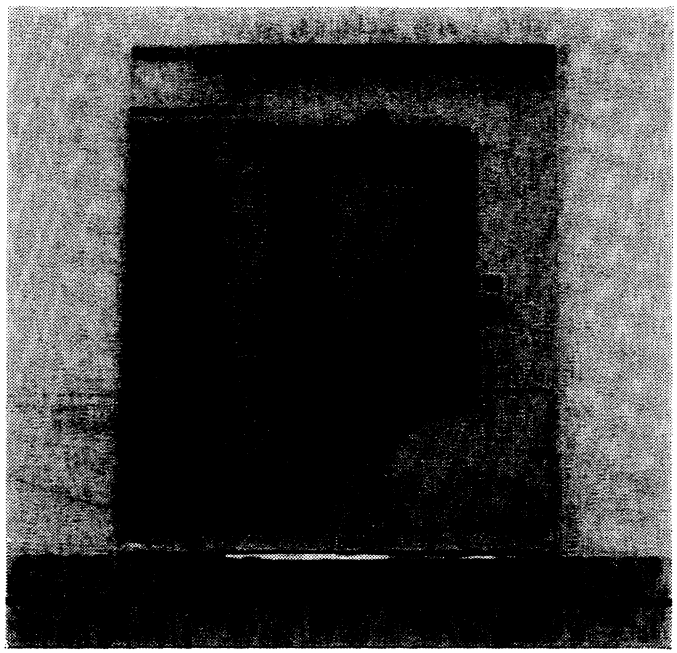

Fig.9 A 2-D NLC array with 1500 elements fabricated at GECRD, showing the compact postage stamp size of the microwave phase control device. (Scale in inches)

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Table 1. The GE-CRD Phase-Based Optically Controlled Phased Array Antenna vs. a Conventional Phase-Shifter-Based Electronically Controlled System

Feature	***Advantage***	***Benefit***
System uses low-cost, mature optical technologies: nematic liquid crystal displays, Bragg cells, fiber optics	Uses readily available off-the-shelf components	Reduces system development costs and overall system cost
≥8-bit analog amplitude and phase control	High-resolution amplitude and phase error calibration capability provides lower antenna sidelobes	Longer radar range, greater target discrimination sensitivity and increased number of beam scan positions
Thousands of digital microwave phase shifters and electrical amplitude trimmers replaced by a pair of postage-stamp-size optical all-analog phase control devices	High pixel packing density of optical device leads to small size; 5,000-antenna-element phase and amplitude control via two 1 × 1 cm liquid crystal devices	Optical devices provides centralized phase and amplitude control in two chips—easy to replace and repair
Phase and amplitude control mechanism insensitive to carrier over wide (4 GHz) frequency change	Intrapulse beamforming capability using long-duration, very wideband signals; stepped frequency chirps	Increased radar range resolution; smaller-sized target detection
Multiband operational range with 4-GHz antenna tunable bandwidth	Same optical hardware used over different frequency ranges	Carrier adaptability to weather, jamming, multipath effects, and target characteristics
Complex microwave feed/splitter network replaced by simple multifiber link	50X reduction in system hardware size and weight; lower EMI	Reduced antenna array weight via smaller-sized antenna backpaneling
Ultra-compact beamformer (3 in. wide × 3 in. high × 12 in. long)	Low system volume appropriate for space-constraint environment	Ideal for mobile platforms—land-, shipboard-, airborne-, and space/satellite-based phased arrays
Lightweight beamformer (5–10 lb)	Increased overall radar system mobility; lower mobility fuel costs	Rapid deployment; reduced payload in airborne-/space-based applications
Beamformer and antenna remotely connected via multifiber link	Centrally located beamformer is easily accessible for monitoring and repair	High EMI at antenna array does not affect remote beamformer
Direct IF-conversion receive technique at antenna element	Prevents propagation of microwave frequency noise through system on receive	Higher signal-to-noise ratio for receiver; longer radar range
Eliminates the 5–6-bit amplitude and phase digital control network at each antenna element required for the thousands of antenna elements	Reduced control hardware at antenna site reduces EMI effects and power consumption	Reduced antenna backpaneling lowers antenna array weight; higher system mobility

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